REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
4 March 1999

3. REPORT TYPE AND DATES COVERED
Final: 30 Sept 1993 - 31 Dec 1998

4. TITLE AND SUBTITLE
Dynamics of Forced Coastal Trapped Disturbances

5. FUNDING NUMBERS
(G)rant
N00014-93-1-1369

6. AUTHOR(S)
Roger M. Samelson and Audrey M. Rogerson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Woods Hole Oceanographic Institution
Mail Stop #21
Woods Hole, Massachusetts 02543

8. PERFORMING ORGANIZATION REPORT NUMBER
131369SP

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217-5660
Attn: Scott Sandgathe
ONR Code 322MM

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Attn: Boston Regional Office

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release, Distribution is Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Numerical and analytical models have been developed and analyzed to study the dynamics of linear and nonlinear coastal-trapped disturbances (CTDs) in the marine atmospheric boundary layer, and the interaction of CTDs with coastal orography and with orographically-modified ambient winds.

14. SUBJECT TERMS
Coastal-trapped disturbances, marine atmospheric boundary layer, orographically-modified winds, idealized numerical model

15. NUMBER OF PAGES
6

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

DTIC QUALITY INSPECTED 2

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

FINAL REPORT
DYNAMICS OF FORCED COASTAL-TRAPPED DISTURBANCES

N00014-93-1-1369
ONR-322MM Award

Audrey M. Rogerson
Physical Oceanography Department
Woods Hole Oceanographic Institution
Woods Hole, MA 02543-1541
Internet: arogerson@whoi.edu
Phone: 508-289-3346
FAX: 508-457-2181

Roger M. Samelson
College of Oceanic & Atmospheric Sciences
Oregon State University
104 Ocean Admin. Bldg.
Corvallis, OR 97331-5503
Internet: rsamelson@oce.orst.edu
Phone: 541-737-4752
FAX: 541-737-2064

LONG-TERM GOAL:

The long-term goal of this project is to improve our ability to understand and predict meteorological conditions in the coastal marine atmospheric boundary layer.

OBJECTIVE:

The objective of this project is to investigate the dynamics of coastal marine atmospheric boundary layer winds including the generation and propagation of coastal-trapped disturbances and their interaction with coastal orography and with orographically-modified ambient winds.

APPROACH:

The approach taken in this project is to obtain analytical and numerical solutions of idealized mathematical models of the marine atmospheric boundary layer and to compare these solutions to observations and to results from more complex models.

WORK COMPLETED:

Numerical and analytical models have been developed and analyzed to study the dynamics of linear and nonlinear coastal-trapped disturbances.

The generation, propagation, and decay of forced linear and nonlinear coastal-trapped disturbances has been studied within a shallow-water framework (Rogerson and Samelson, 1995; Samelson and Rogerson, 1996; Rogerson, 1999b). The vertical structure of linear coastal-trapped disturbances was analyzed for models with continuous and two-layer stratification (Samelson, 1999).

Numerical model solutions of hydraulically supercritical and subcritical shallow-water flows have been computed for domains with irregular coastline geometry using modern numerical techniques. The nonlinear interaction of coastal-trapped disturbances and transcritical steady-state flows has been analyzed (Rogerson, 1999a). Hydraulically transcritical model flows have been computed for comparison with observational data from the 1996 Coastal Waves Experiment along the California coast.

Mesoscale simulations of the interaction of continuously stratified, hydraulically supercritical and transcritical flow with coastal orography have been carried out and analyzed, yielding new insight into the dynamics of coastal winds (Burk et al., 1999).

This grant has also provided partial support for studies of the coastal ocean response to wind forcing (Samelson, 1997), for a theoretical and numerical investigation of Lagrangian transport in a meandering jet (Rogerson et al., 1999; Lozier et al., 1997; Miller et al., 1997), and for a numerical study of planetary geostrophic ocean circulation (Samelson, 1998).

RESULTS:

Results from the forced linear shallow-water model reveal that the coastal-trapped disturbance has several distinct phases and components (Rogerson and Samelson, 1995; Samelson and Rogerson, 1996). Initially, the marine layer thickness at the coast responds to convergence of ageostrophic cross-shore flow near the center of the low-pressure forcing, and to geostrophic cross-shore convergence and divergence to the south and north, respectively, with little indication of propagation. As the forcing moves away from the coast, the disturbance resembles a damped Kelvin wave. The superposition of cross-shore propagating forcing and the northward-propagating disturbance can give rise to surface pressure ridges at the coast with both narrow and broad cross-shore extent. The alongshore length scale of the disturbance depends on the propagation speed of the forcing, and may appear more mesoscale-like for fast-moving pressure systems. The results from the linear forced model agree qualitatively with many aspects of observed coastal-trapped wind-reversal events.

Results from the forced nonlinear model demonstrate that the nonlinear response to different time-dependent forcing scenarios can produce coastal-trapped disturbances that display a wide variety of characteristic features (Rogerson, 1999b). In addition to the expected steepening of the leading edge of the disturbance wave, the nonlinear dynamics include enhanced dissipation when the marine layer thickness is small, resulting in a disturbance that quickly evolves into a wave of elevation only. The alongshore and cross-shore structure of the response are affected by time-dependent variations in the forcing, which in turn influence the propagation speed of the freely-propagating disturbance. As a result, the profile of the disturbance can differ significantly from the "typical" nonlinear Kelvin wave profile.

The analysis of the vertical structure of coastal-trapped disturbances has shown that the presence of a stable layer above the boundary layer inversion increases the gravest mode phase speed and supports the existence of higher modes (Samelson, 1999). Results from the two-layer study suggest that the observed vertical structure of isotherms at the leading edge of the 10-11 June 1994 event may arise during a transition from a directly forced, barotropic, alongshore velocity response to a regime dominated by wave propagation, as coastal-trapped vertical modes excited by mesoscale pressure gradients begin to disperse at their respective phase speeds.

The numerical investigation of hydraulically transcritical shallow-water model flows has described the spatial structure of steady-state flows corresponding to different levels of constant pressure-gradient forcing, and the interaction of coastal-trapped disturbances with the steady base flows (Rogerson, 1999a). The steady-state flows are hydraulically supercritical in the region where the coastline geometry is irregular, but are subcritical offshore and where the coastline is straight. In the supercritical region, the flow exhibits expansion fans and compression jumps at convex and concave coastline bends, respectively. Perturbations in the marine layer that originate in a subcritical region can propagate northward as coastal-trapped waves, relaxing or reversing the alongshore northerly winds, but can be halted near coastline bends by supercritical flow conditions. The interaction of strong coastal-trapped disturbances with supercritical regions of the flow is accompanied by an eddy-generation process that resembles satellite images of stratus during the observed May 1982 coastal-trapped event off California (Figure 1).

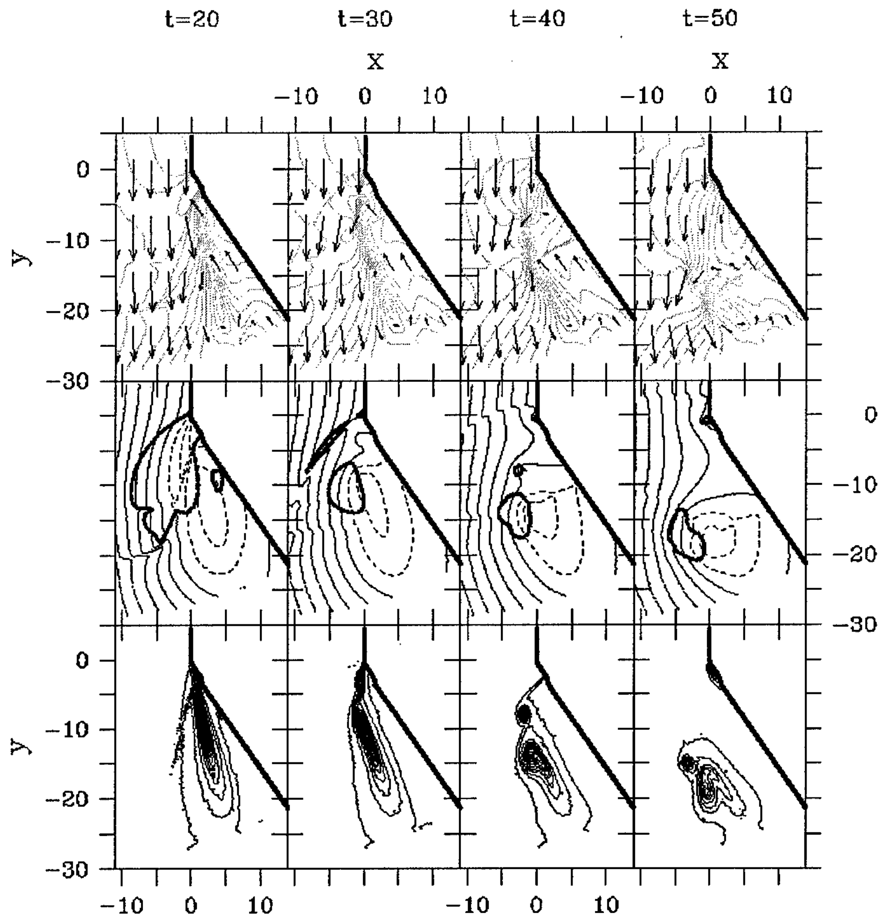

Figure 1: Interaction of a coastal-trapped disturbance with a transcritical base flow. [1st row] Velocity vectors and contours of wind speed; [2nd row] contours of layer thickness and region of criticality (delineated by the thick line); [3rd row] contours of potential vorticity. (From Rogerson (1999a).)

Numerical solutions of a nonlinear shallow-water model are being utilized to aid the dynamical interpretation of aircraft observations from the 1996 Coastal Waves field experiment in the vicinity of Cape Mendocino. The modeling study indicates that the flow downstream of the Cape is supercritical even when the upstream winds are only moderately strong, resulting in acceleration of the wind and a decrease in inversion height south of the Cape. The effect can be strong enough to cause flow separation in the vicinity of Shelter Cove, which is consistent with observations of weak winds nearshore within the Cove concomitant with very strong winds further offshore. This work is being conducted in collaboration with K. Edwards and C. Winant of the Scripps Institution of Oceanography.

Mesoscale atmospheric model simulations of the interaction of stratified hydraulically supercritical and transcritical flow with coastal orography revealed horizontal structure similar to that found previously in observations and in shallow-water models of supercritical and transcritical flow along a varying coastline (Burk et al., 1999). However, a significant response in the stratified flow above the marine atmospheric boundary layer inversion was also observed in the simulations, a feature that is not represented in the simpler shallow-water case. Analysis of these simulations in terms of a shallow-water similarity theory implicated the vertical shear, rather than the stratification, as the dominant vertical trapping mechanism, giving new insight into previous shallow-water theories of this phenomenon. This work was conducted jointly with S. Burk and T. Haack at the Naval Research Laboratory, Monterey, using the mesoscale atmospheric model COAMPS.

Numerical solutions of a multi-layer primitive equation model with idealized topography, forced by fields derived from the NCEP Eta analysis during 9-12 June 1994, have been obtained to investigate the dynamics of the observed 10-11 June 1994 coastal-trapped disturbance. The results indicate the presence of both directly forced and propagating-wave components in the response, and suggest that leakage of low-level marine air over the coastal orography may limit the amplitude of the trapped response.

Analysis of the wind-forced response of a two-layer coastal ocean model in the 2-7 day period band and comparison with CODE observations gave new insights into inner-shelf dynamics (Samelson, 1997). In this model, the upper layer represented a surface wind-mixed layer. For the alongshore velocity gain relative to local wind stress, an onshore surface maximum and an offshore interior maximum were robustly reproduced by the model. These features are evidently related to a dynamical transition over the inner half of the northern California shelf, in which the alongshore wind stress is balanced more by acceleration of near-surface alongshore flow, and less by time-dependent Ekman transport as the coast is approached. This differs from a previous hypothesis, based on a linear model in which the turbulent stress was confined to infinitesimally thin surface and bottom boundary layers, which related the alongshore flow structure to cross-shore variations in the alongshore wind amplitude. These results emphasize that the analysis of inner-shelf ocean dynamics depends on accurate knowledge of the wind stress over the inner shelf.

The investigation of Lagrangian transport in a numerically-modeled meandering jet has shown that there is significant fluid exchange between the model jet and its surroundings due to the temporal variability of the flow (Rogerson et al., 1999; Lozier et al., 1997; Miller et al., 1997). The analysis demonstrated the application of dynamical systems techniques to a model flow that is aperiodic and available only over a finite time, and revealed the geometrical structures that demarcate regions of strong fluid filamentation and possible mixing (Figure 2). When the results are applied to the Gulf Stream, the fluid exchange occurring along the flanges of the jet is comparable to the transport associated with the detachment of Gulf Stream rings.

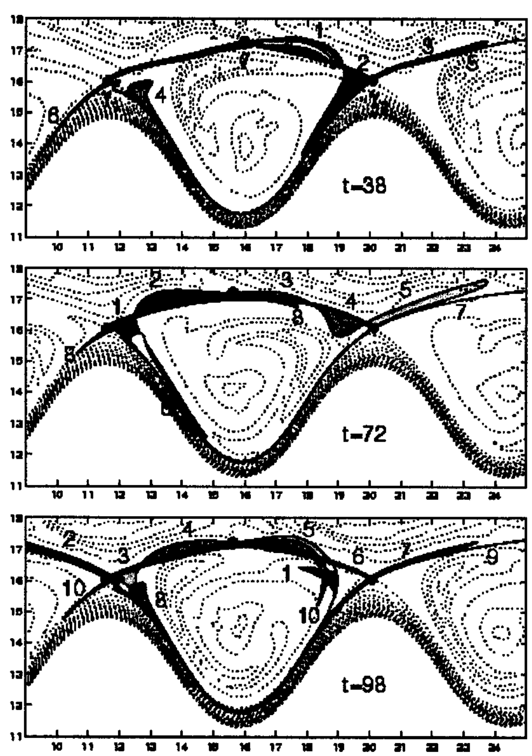

Figure 2: Potential vorticity contours (dashed lines) on the northern side of a meandering jet and geometrical structures (solid lines) that demarcate blobs of fluid (colored) that undergo strong filamentation. (Adapted from Rogerson et al., (1999).)

The planetary geostrophic calculations indicate that intense boundary mixing over broad areas is necessary to support deep stratification comparable to observed values in a single-hemisphere, closed-basin model (Samelson, 1998), but can be achieved with uniformly small diffusivity in a channel geometry if friction is also small. The circulation induced by the localized mixing, with warming and upwelling in the mixing region of cold fluid that enters the abyss from a single dense source, appears broadly consistent with recent estimates from of mixing and circulation of Antarctic Bottom Water in the Brazil Basin.

IMPACT/APPLICATIONS:

Results from this theoretical and numerical modeling effort will contribute to the overall goal of improving weather prediction models through enhanced understanding of the dynamics that control coastal meteorological conditions.

TRANSITIONS:

RELATED PROJECTS:

This work is part of the ONR Coastal Meteorology ARI (Nuss et al., 1999).

PUBLICATIONS:

Burk, S. D., T. Haack, and R. M. Samelson, 1999. Mesoscale simulation of supercritical, subcritical, and transcritical flow along coastal topography. *J. Atmos. Sci.*, in press.

Lozier, M. S., L. J. Pratt, A. M. Rogerson, and P. D. Miller, 1997. Exchange geometry revealed by float trajectories in the Gulf Stream. *J. Phys. Oceanogr.*, 27, 2327-2341.

Miller, P. D., C. K. R. T. Jones, A. M. Rogerson, and L. J. Pratt, 1997. Quantifying transport in numerically-generated velocity fields. *Physica D*, 110, 105-122.

Nuss, W., J. Bane, W. Thompson, T. Holt, C. Dorman, F. M. Ralph, R. Rotunno, J. Klemp, W. Skamarock, R. Samelson, A. Rogerson, C. Reason, P. Jackson, 1999. Coastally trapped wind reversals: progress toward understanding. To be submitted to *Bulletin of the American Meteorological Society.*

Rogerson, A. M., 1999a. Transcritical flows in the coastal marine atmospheric boundary layer. *J. Atmos. Sci.*, in press.

Rogerson, A. M., 1999b. Life cycles of nonlinear coastal-trapped disturbances. *Mon. Weather Rev.*, submitted.

Rogerson, A. M., and R. M. Samelson, 1995. Synoptic forcing of coastal-trapped disturbances in the marine atmospheric boundary layer. *J. Atmos. Sci.*, 52, 2025-2040.

Rogerson, A. M., P. D. Miller, L. J. Pratt, C. K. R. T. Jones, 1999. Lagrangian motion and fluid exchange in a barotropic meandering jet. *J. Phys. Oceanogr.*, in press.

Samelson, R. M., 1997. Coastal boundary conditions and the baroclinic structure of wind-driven continental shelf currents. *J. Phys. Oceanogr.*, 27, 2645-2662.

Samelson, R. M., 1998. Large-scale circulation with locally enhanced vertical mixing. *J. Phys. Oceanogr.*, 28, 712-726.

Samelson, R. M., 1999. The vertical structure of linear coastal-trapped disturbances. *Mon. Weather Rev*, 127, 201-213.

Samelson, R. M., and A. M. Rogerson, 1996. Life-cycle of a linear coastal-trapped disturbance. *Mon. Weather Rev*, 124, 1853-1863.